To Protect Quantum Information, Understand What Threatens it

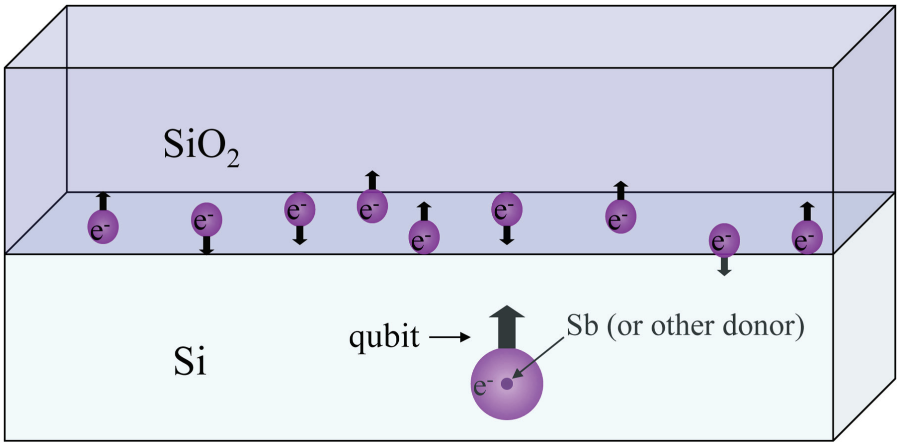

Figure 1: Decoherence of a donor qubit in silicon from a surface of electrons at random defect sites.

Progress is being made in understanding how qubits loose their information during interactions with system noise.

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The famous physicist Richard Feynman surmised that a computer engineered to exploit quantum phenomenon (i.e., a quantum computer) could be vastly more powerful than a classical computer. However, the feasibility of building a quantum computer was not broadly accepted until Peter Shor discovered a means for quantum error correction despite the limitation that quantum information cannot be fully copied nor measured. Shor also devised a quantum algorithm for factoring integers that had an exponential improvement over the best-known classical algorithm, with important implications for cryptography and national security. Since then, dozens of quantum algorithms have been developed and quantum information theory has progressed sufficiently that it is now practical to address the engineering problem of building a quantum computer.

A primary problem for quantum computing is to devise practical physical means of storing quantum computational binary digits, or *qubits*. Any two-level quantum mechanical system can serve as a qubit. There are many proposed systems involving states of photons, electrons, nuclei, atoms, or even superconducting circuits. A general problem is that the qubits must maintain their quantum information for usefully long periods of time (milliseconds), relative to the duration of logical gate operations. The culprit in the loss of qubit information, quantum decoherence, must be understood and minimized. For this reason, Sandia has developed computational methods to simulate potential sources of decoherence, and thus give guidance to how experimental qubit fabrication can best be improved.

At Sandia, an effort is underway to develop a qubit from the spin of a localized electron in a silicon crystal, either in an electrostatically-confined quantum dot or bound to a donor such as antimony (Sb, see Figure 1). Since this qubit must be sufficiently isolated to preserve its information for milliseconds, understanding decoherence in this system as a function of time is critically important. In particular, the electron spin is susceptible to magnetic fields from nuclear spins or other electron spins, which fluctuate due to interactions

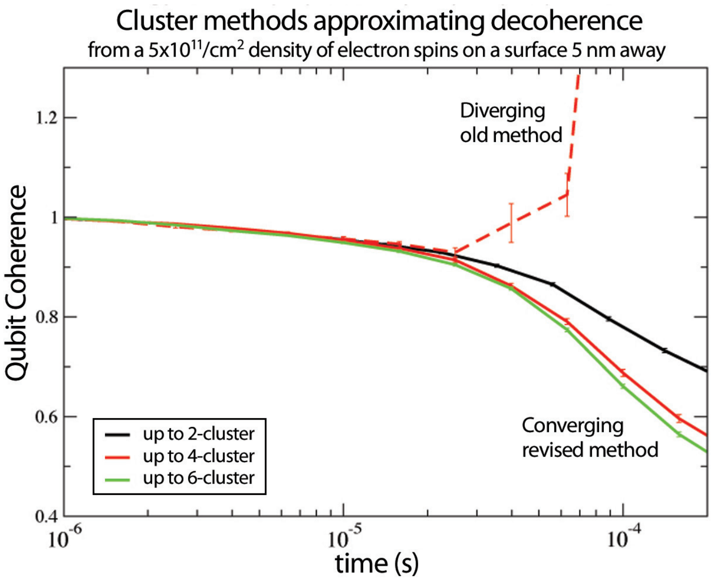

Figure 2: Revised cluster methods have made it possible to study problems of sparse electron spins baths.

with each other. Therefore, it is necessary to simulate the system of a spin qubit within a bath of many environmental spins interacting with each other through mutual magnetism. This presents the exponentially-scaling difficulty of simulating a quantum system.

Fortunately, one only needs to compute information about the initial coherence loss of the qubit. Processes involving two spins will occur before processes involving more spins, and the initial coherence loss can be analyzed very well using a mathematical cluster expansion that successively includes processes involving an increasing number of spins. In this way, the computation no longer scales exponentially with the size of the problem; rather, it scales exponentially with the required cluster size. The cluster expansion works particularly well for the problem of an electron spin that is strongly coupled to a large number of nuclear spins through direct contact (hyperfine) interactions. The nuclear spins have relatively weak magnetic interactions with each other, and a strong external magnetic field is applied. The full coherence decay can be well-approximated with clusters of only two spins (Reference 1). The cluster correlation expansion was later developed (Reference 2) to extend the method to the regimes of a sparse bath and is a cleaner formulation that is always exact in the large cluster limit.

The current research involves a sparse bath of electron spins where interactions with the qubit spin are no stronger than interactions among bath spins. In Reference 3, decoherence induced from spins of electrons bound to a background of phosphorus donors in bulk silicon is considered. An example is illustrated in Figure 1, where a surface of electrons at defects along an interface may induce decoherence of a qubit through their spin interactions. In these problems, larger clusters do play a more important role. This new regime also necessitates some revisions of the cluster correlation expansion formalism. In particular, good convergence is not achieved until one averages over the state of some of the spins that are external to a given cluster in a self-consistent matter; this stabilizes the random effects of a sparse bath (Figure 2). Sandia continues to extend these techniques in an effort to understand and then mitigate sources of decoherence that hinder progress on quantum computation.

References

1. W. M. Witzel, Decoherence and Dynamical Decoupling in Solid-State Spin Qubits, http://hdl.handle.net/1903/6889 (dissertation, 2007); W. M. Witzel, R. de Sousa, S. Das Sarma, Quantum theory of spectral diffusion induced electron spin decoherence, *Phys. Rev* B **72**, 161306(R) (2005); W. M. Witzel, S. Das Sarma, Quantum theory for electron spin decoherence induced by nuclear spin dynamics in semiconductor quantum computer architectures: Spectral diffusion of localized electron spins in the nuclear solid-state environment, *Phys. Rev.* B **74**, 035322 (2006). W. M. Witzel and S. Das Sarma, Multiple-pulse coherence enhancement of solid state spin qubits, *Phys. Rev. Lett.* **98**, 077601 (2007).
2. Wen Yang and Ren-bao Liu, Quantum many-body theory of qubit decoherence in a finite-size spin bath, *Phys. Rev.* B **78**, 085315 (2008).
3. Wayne M. Witzel, Malcolm S. Carroll, Andrea Morello, Lukasz Cywinski, and S. Das Sarma, Electron spin decoherence in isotope-enriched silicon, arXiv:1008.2382.

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